



Fermi National Accelerator Laboratory

FERMILAB-Conf-93/238

Recent Fermilab Results on Hadroproduction of Heavy Flavors

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August 1993

Invited talk presented at *HADRON '93 Conference, Centro di Cultura Scientifica "A. Volta", Villa Olmo, Como, Italy, June 21-25, 1993*. Proceedings to be published in *Il Nuovo Cimento*

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Summary. - Recent results from various Fermilab experiments on the hadroproduction of states containing charm, bottom, and top quarks are discussed. These include observation of the spectra, lifetimes, and production characteristics of charmonium, open charm states, and bottom particle production with both high energy fixed target and $\bar{p} - p$ collider facilities. The status of the search for the top quark by the Fermilab collider experiments is updated.

PACS 13.20.Fc, 13.85.Ni, 13.85.Qk, 13.85.Rm, 14.40.Jz

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1 Introduction

The Fermilab 1990-91 Fixed Target Physics run and the recently ended 1992-93 $\bar{p} - p$ collider run have produced a wealth of new physics results. New results on the hadroproduction of heavy quarks (c , b , and t) have been reported by E-653, E-672, E-705, E-769, E-771, E-772, E-789, E-791, CDF, and D-Zero. Other invited speakers at this conference [1] discussed the charm photoproduction experiment E-687 and the low energy $\bar{p} - p$ charmonium spectroscopy experiment E-760 in more detail.

2 Charm Particles

2.1 Hadroproduction of Charm

Recent results on the production of charm particles by hadron beams have been provided by E-653 [2] and E-769 [3]. These included the x_{feynman} , p_{\perp} , and nuclear target A-dependences for D^+ , D^0 and D^{*+} and their charge conjugates. Due to space limitations, I will have to point the reader to the references and to an excellent recent review article [4] and summary talk [5].

2.2 Leptonic Decays of D_s^+

E-653, using both π^- and p beams in a hybrid emulsion spectrometer, has observed the purely leptonic decay $D_s^+ \rightarrow \mu^+ \nu_\mu$ through annihilation of the c and the \bar{s} quarks [6]. The p_{\perp} spectra of the μ^+ relative to the direction of the D_s^+ observed in the emulsion is shown in Figure 1a. The small peak of about 20 events extending beyond the kinematic limit for D^0 or $D^+ \rightarrow \mu^+ X$ constitutes the first observation of $D_s^+ \rightarrow \mu^+ \nu_\mu$. Figure 1b also shows one of three examples of events interpreted as the decay $D_s^+ \rightarrow \tau^+ \nu_\tau$, followed by a one-charged-body decay of the τ lepton. This observation relies on the ability of the emulsion to observe the directions of the D_s^+ and the τ^+ and the small decay kink between them. This demonstrates the capability of the

emulsion technique to observe the τ produced in charged current weak interactions of ν_τ arising from neutrino oscillations. Given sufficient statistics, these observations of both $D_s^+ \rightarrow \mu^+ \nu_\mu$ and $\tau^+ \nu_\tau$ could serve as another test of lepton universality in weak interactions.

3 Charmonium

There are new results in both the production and spectroscopy of charmonium states using high energy p and π^- beams. These experiments detect the decay $J/\psi \rightarrow \mu^+ \mu^-$, along with additional photons to study χ_c states, or along with additional hadrons for spectroscopy studies.

3.1 Why is hadro-production of χ_c Interesting?

Theoretically, the hadro-production of χ_c states must proceed through multi-gluon processes, but the final $c-\bar{c}$ state must somehow emerge colorless. Since there are differences in production by p and by π beams, we know that the valence quarks must also play an important role. Finally, the study of processes involving χ_c can provide insight into the underlying gluonic structure of the interacting hadrons.

There are three classes of models for hadroproduction of χ_c states [7]. These are sketched in Figure 2 and can be described under the broad headings of gluon fusion, quark fusion, and evaporation diagrams. Each class of model makes definite predictions as to the relative production of χ_{c0} , χ_{c1} , and χ_{c2} states. Unfortunately, the χ_{c0} state is not readily accessible due to its low branching fraction into γ plus J/ψ .

3.2 Experiments and Results on Production Dynamics

E-672 [8] uses a 530 GeV π^- beam with either Be or Cu targets along with a di-muon trigger spectrometer. For the study of χ_c states, the decay gamma ray is required to convert into an e^+e^- pair in the target region and be reconstructed by the E-706 multiparticle spectrometer. Examples of the signals and resolutions obtained by E-672 are shown in Figure 3. Note in particular that the χ_{c1} and χ_{c2} states are resolved.

E-705 [9] presents results using 300 GeV p , π^- , and π^+ beams incident on a Li target, using a conventional multiparticle spectrometer with downstream muon trigger/detector walls. Their gamma ray detector consisted of a scintillating glass and lead glass counter array with active converters for improved spatial position resolution. Examples of E-705's signals and resolutions are given in Figure 4. In particular, note that the χ_{c1} and χ_{c2} states are not resolved by E-705. The components of the χ_c peak are fitted, leading to correlated errors for χ_{c1} and χ_{c2} . In addition to reporting cross sections for production of charmonium integrated over the forward hemisphere, as for E-672, E-705 also reports the $x_{Feynman}$, p_\perp , and beam species dependences for J/ψ , ψ' , and χ_c .

Table 1 compares various integrated charmonium cross sections as measured by E-672 and E-705. Figure 5 compares the fraction of J/ψ produced via χ_c measured by various experiments [10]. Figure 6 compares the hadroproduction ratio of χ_{c1}/χ_{c2} for measurements and model predictions. The color evaporation models are consistent with χ_c production ratios for

pion beams, whereas, the E-705 data, albeit with low statistical separation, indicates that the gluon fusion model prediction is favored for production with proton beams.

E-772 [11] used a high intensity 800 GeV primary proton beam and the E-605 spectrometer to perform a high sensitivity study of the nuclear target dependence of the production of J/ψ , ψ' , Υ , and Drell-Yan $\mu^+\mu^-$ pairs. The nuclear dependence parameter α was studied as functions of p_\perp , x_{feynman} , and x_2 , the momentum fraction of the interacting parton within the nuclear target. By studying the Drell-Yan process, a limit on the $\bar{d}_p(x)/\bar{u}_p(x)$ asymmetry for the sea anti-quark distributions in the nucleon was obtained. Please see reference [11] for full discussion of these E-772 results.

3.3 Charmonium Spectroscopy

E-760 [12] recently observed a narrow resonance in the exclusive production reaction $\bar{p}p \rightarrow J/\psi \pi^0$ at a mass of 3.526 GeV which they interpret as the 1P_1 charmonium state. E-705 has searched [13] for similar charmonium resonances in decays into J/ψ (or ψ') plus additional π 's. In Figure 7a, they see a 2.5σ peak (42 ± 17 events) in the $J/\psi \pi^0$ mass spectrum at 3.527 ± 0.008 GeV, which confirms the E-760 observation. In the $J/\psi \pi^+\pi^-$ mass spectrum, Figure 7b, E-705 observes not only the ψ' , but also structure at 3.836 ± 0.013 GeV (58 ± 21 events), at least for the π^- beam data. They speculate that this could be the $^3D_2(2^{--})$ state, but warn that this observation requires confirmation. E-672, for example, with an equivalent ψ' sample in Figure 3, does not see such an enhancement. E-705 searched for, but did not observe any structure in $J/\psi \pi^\pm\pi^\pm$, $J/\psi \pi^\pm\pi^0$, or $\psi' \pi^\pm$.

4 Fixed Target Bottom

Four fixed target experiments are designed to study production of bottom particles. E-653 and E-672 are complete and have been presenting results. E-789 and E-771 [14] have had test runs trying to develop techniques to study short decay topologies at high interaction rates.

E-653 [15] used a 600 GeV π^- beam in an emulsion target followed by a multiparticle spectrometer with silicon vertex detector and a high p_\perp muon trigger. b -particles are identified in the emulsion by decay topologies. E-653 has obtained data on the total $b\bar{b}$ cross section

$$\sigma_{\pi^- \text{ Em} \rightarrow b\bar{b}X} = 33 \pm 11(\text{stat.}) \pm 6(\text{syst.}) \text{ nb/nucleon at } \sqrt{s} = 33.5 \text{ GeV},$$

x_{feynman} and p_\perp distributions, and b -lifetimes. Based on a sample of 13 $b\bar{b}$ pairs, E-653 finds the proper decay time distribution, Figure 8, and the average lifetimes of

$$\tau(\text{neutral } B) = 0.86^{+0.32+0.09}_{-0.21-0.02} \text{ psec (15 decays) and}$$

$$\tau(\text{charged } B) = 3.6^{+1.7+1.4}_{-1.0-0.2} \text{ psec (11 decays).}$$

E-672 [16] used their di-muon spectrometer and the E-706 multiparticle spectrometer and silicon vertex detector to search for events with a J/ψ decaying into $\mu^+\mu^-$ downstream of the primary vertex. Figure 9a shows the decay length distribution of these detached decay vertex

J/ψ b -candidates. E-672 further required that the J/ψ decay occur outside of the target material as in Figure 9b. Based on the 9 ± 3 remaining candidates, E-672 was able to quote a total cross section for b -production

$$\sigma_{\pi^-A \rightarrow b\bar{b}X} = 43 \pm 13_{-13}^{+16} \text{ nb/nucleon at } \sqrt{s} = 31.5 \text{ GeV.}$$

In Figure 10a, these Fermilab data are compared to that of the earlier CERN multi-muon experiment WA-78 [17] and a range of theoretical predictions [18].

E-672 also has added charged K and K^{*0} to their detached vertex J/ψ and observe 5 exclusive b -candidates, Figure 10b, consistent with the mass of the B^+ and B^0 .

In a test for future high luminosity fixed target experiments, specifically to search for two-body decays of bottom, E-789 [19] used the E-605 two arm spectrometer with a silicon vertex detector to observe interactions of primary 800 GeV protons in a 3 mm gold target at a rate of 50 million interactions per second. Their excellent mass resolution and ring imaging cerenkov counter allowed them to reconstruct the two-body decays $D^0 \rightarrow K^-\pi^+$, $\pi^+\pi^-$, and K^-K^+ in Figure 11, albeit with large reflection peaks due to particle mis-identification. E-789 also demonstrated the capability of the vertex detector by measuring the lifetime of the D^0 to be $\tau(D^0) = 0.41 \pm 0.03 \text{ psec}$. By varying decay position cuts for the $J/\psi \rightarrow \mu^+\mu^-$ outside of the Au target in Figure 12, E-789 finds a excess of long-lived J/ψ events, which are interpreted as b -particle candidates.

5 Collider Bottom

5.1 Introduction

$\bar{p} - p$ hadron colliders are a good source of bottom particles. The available energy, the interaction rates and luminosities, and the b -production cross section are all large. However, the b -particles are produced against a large background of many other physics processes, not like for the exclusive production at e^+e^- collider experiments ARGUS and CLEO running on the $\Upsilon(4S)$ resonance, and not quite like for the LEP e^+e^- experiments running on the Z^0 where the $b\bar{b}$ production ratio is high (22 %), and where the fragmentation of the b -quark into mesons and baryons is hard. The topics studied by all of these experiments are similar, namely the cross section for $b\bar{b}$ production, b -particle spectroscopy, including masses, exclusive and inclusive decays, branching fractions, lifetimes, and mixing in the $B^0 - \bar{B}^0$ system. The b -particles can be signatures of the production and decay of the top quark. Finally, the current experiments are just the initial steps, developing the techniques necessary for the study of CP -violation in the b -system.

5.2 Techniques

The techniques for studying b -physics at a hadron collider are many and varied. The highest rate approach is to study single leptons from the inclusive semi-leptonic decays of b . At high p_\perp , most of the leptons are expected to be from b decays. However, there are still questions of large backgrounds, understanding detector thresholds, and other systematic obstacles to this

approach. An associated technique is to observe correlations in charge between single, high p_{\perp} leptons and charm particles or baryons. Finally, there is the study of correlations of two opposite sign di-leptons, one each from the b and \bar{b} decays. This is a way to also study mixing, however the signals are diluted or confused by (lower p_{\perp}) leptons from the decay of charm particles which were themselves products of the original b decays. Inclusive production of J/ψ , ψ' , or χ_c at high p_{\perp} from b decays can be used to measure the $b\bar{b}$ cross section. Recently, the use of high resolution vertex detectors to separate the decay vertex of the b -particle, often into a J/ψ , from the primary interaction vertex, has given estimates of the inclusive b -particle lifetime. By adding in additional mesons to the detached vertex J/ψ , one can study the exclusive decays, the masses, and the lifetimes of individual B^+ , B_d^0 , and B_s^0 mesons, and possibly also b -baryons.

5.3 The Fermilab Collider Experiments

The two large multi-purpose collider detectors at Fermilab, CDF [20] and D-Zero [21], ended a year-long run on June 1, 1993. This was the first run for the new D-Zero experiment. CDF had previously run in the 1988-89 timescale. The major new CDF component for b -physics added for the 1992-93 run was the SVX silicon vertex detector [22] shown in Figure 13a. This detector consists of 4 concentric layers of 60 μ wide silicon strips, giving readout in the $r - \theta$ coordinates (not z). The inner SVX plane is at a radial distance of 2.9 cm from the p and \bar{p} beams. Figure 13b also displays an interesting event with three separate vertices. The D-Zero detector has been optimized for high p_{\perp} physics and does not have either a magnetic field or a vertex detector, so it is now at a relative disadvantage with respect to the study of b -physics. Upgrades have been proposed to improve the D-Zero capabilities in these areas.

5.4 b -physics Results from CDF

A sample of b -physics results from CDF, based on the 1988-89 run and on analysis of approximately one-half of the data from the 1992-93 run is presented. D-Zero is just getting started in this area.

The integrated cross section [23] for the $\bar{p} - p$ production of b -particles in the central region as a function of the p_{\perp} acceptance threshold is depicted in Figure 14a. The cross section for a given detection channel is quoted for values of $p_{\perp} \geq p_{\perp min}$, typically 8 Gev or so. Extrapolating to all p_{\perp} with pseudo-rapidity $|\eta| \leq 1$ gives the $\sigma_b \approx 20 \mu barn$, just within this restrictive η range.

The 'average' lifetime of the b -particle is measured by observing the decay length distribution of detached J/ψ vertices [24]. The decay length for a given candidate is then converted to a 'pseudo-proper time' using a simulated correction model and the measured J/ψ momentum. Figure 14b shows this distribution including the component due to the decay distribution of the sidebands in the J/ψ mass distribution. The average CDF measured b -particle lifetime based on this inclusive, detached J/ψ sample is

$$\langle \tau(b\text{-particle}) \rangle = 1.46 \pm 0.06 \pm 0.06 \text{ psec},$$

compared with the LEP average [25] of $1.40 \pm 0.04 \text{ psec}$, and the PDG average [26] of $1.29 \pm 0.05 \text{ psec}$. Using similar detached vertex techniques [27], Figure 15 for $B^+ \rightarrow \psi K^+$,

$B^+ \rightarrow \psi K^{*+}$, $B^+ \rightarrow \psi' K^+$, $B^+ \rightarrow \psi' K^{*+}$, $B^0 \rightarrow \psi K_s^0$, $B^0 \rightarrow \psi K^{*0}$, $B^0 \rightarrow \psi' K_s^0$, and $B^0 \rightarrow \psi' K^{*0}$, where $\psi \rightarrow \mu^+ \mu^-$, $\psi' \rightarrow \psi \pi^+ \pi^-$, $K^{*+} \rightarrow K_s^0 \pi^+$, $K^{*0} \rightarrow K^+ \pi^-$, and $K_s^0 \rightarrow \pi^+ \pi^-$, CDF finds

$$\begin{aligned}\tau(B^+) &= 1.63 \pm 0.21 \pm 0.16 \text{ psec}, \text{ and} \\ \tau(B^0) &= 1.54 \pm 0.22 \pm 0.10 \text{ psec},\end{aligned}$$

giving the CDF ratio of lifetimes for the charged and neutral B as

$$\tau(B^+)/\tau(B_d^0) = 1.06 \pm 0.20 \pm 0.12 \quad ,$$

to be compared to the LEP average ratio [25] of $1.00^{+0.17}_{-0.14}$ and the PDG average ratio [26] of 0.93 ± 0.16 .

CDF [28] has observed not only the exclusive decays $B^+ \rightarrow \psi K^+$ and $B_d^0 \rightarrow \psi K^{*0}$, but now also 14 ± 5 events of the decay $B_s^0 \rightarrow \psi \phi$, as shown in Figure 16. This gives a mass difference

$$\Delta M = M(B_s^0) - M(B_d^0) = 103.7 \pm 5.4 \text{ MeV for CDF},$$

compared to the similar $\Delta M = 87 \pm 6 \text{ MeV}$ for LEP [29], based on a total of 13 B_s^0 decays from ALEPH and DELPHI, distributed over the decay channels $\psi' \phi$, $D_s^+ \pi^-$, $D_s^+ a_1$, $\psi K K \pi \pi$, $\psi \phi$, and $D^0 K \pi \pi \pi$. The CUSB experiment [30], in observing the spectra of γ 's in association with J/ψ , found a two-fold ambiguity in the solution for this same mass difference, namely $\Delta M = 82.5 \pm 2.5 \text{ MeV}$, or $\Delta M = 121 \pm 9 \text{ MeV}$.

6 The Search for Top

6.1 Expected Characteristics of top

The top quark and the ν_τ are the two yet unobserved members required to round out the third generation of quarks and leptons. It is known that the top is heavy [31], with $m_{top} \geq 91 \text{ GeV}$, and definitely $m_{top} > m_{W^\pm}$. To maintain consistency with the observations of neutrino experiments, hadron colliders, and the electro-weak parameters measured at LEP [32], the standard model would expect the m_{top} to be in the 100 - 160 GeV range, using an assumed $m_{higgs} = 300 \text{ GeV}$. At this time, only the Fermilab $\bar{p} - p$ collider has sufficient energy and luminosity reach to search in this mass range. If the m_{higgs} were to be 1000 GeV, then this range of m_{top} would increase to 125 - 175 GeV.

Since $m_{top} > m_{W^\pm}$, the dominant decay mode is $t \rightarrow b + W^+$, where the b can be manifested as a jet or can decay $b \rightarrow c + \ell^- + \nu_\ell$. The W^+ can decay, with the indicated branching fractions, into $e\nu(1/9)$, $\mu\nu(1/9)$, $\tau\nu(1/9)$, $u\bar{q}(3/9)$, or $c\bar{q}(3/9)$. The extra factor of 3 in the branching fractions for the decay into quarks is due to the color degree of freedom. Again, since $m_{top} > m_{W^\pm}$, the top must be produced in pairs, leading to the final states $t\bar{t} \rightarrow bW^+ \bar{b}W^-$. The searches described here will concentrate on the states and branching fractions: $b\bar{b}e^+e^-(1/81)$, $b\bar{b}\mu^+\mu^-(1/81)$, and $b\bar{b}e^\pm\mu^\mp(2/81)$. The decay products of the b and \bar{b} are not necessarily observed for this analysis which relies on the observation of inclusive high p_\perp opposite-sign di-lepton pairs.

There is extensive work being done to develop the analyses for single high p_{\perp} lepton + Jets (12/81 e^{\pm} and 12/81 μ^{\pm}) and for ‘tagging’ the top event candidates through the b -decay observed in the SVX vertex detector. Analysis of the more difficult inclusive $\tau^{\pm} + X$ (17/81) and the all Jet (36/81) final states is just getting going.

6.2 Experimental Results on top

Both CDF [33] and D-Zero [34] present preliminary results on the search for top in the dilepton mode, based on analysis of approximately one-half of the integrated luminosity for the 1992-93 run. The analysis cuts are listed in Table 2. These cuts required both observed high p_{\perp} leptons to be in the central region of rapidity space, with large missing transverse energy, isolated from hadron jets, and not consistent with decay from a Z^0 . Both CDF and D-Zero observe one candidate event each satisfying these cuts depicted in Figure 17. Backgrounds expected from various physics sources and instrumental effects have been estimated. CDF expects 1.5 background event and D-Zero expects 0.85 background event in this sample. Table 3 summarizes these statistics and indicates the number of $t\bar{t}$ events expected to be observed for these luminosities and these acceptances and analysis cuts for a hypothesized m_{top} . After including the one top -candidate event from its 1988-89 run [31], CDF finds a 95 % confidence limit $m_{top} \geq 108$ GeV based on the theoretical model [35] for the production rate $\sigma(p\bar{p} \rightarrow t\bar{t}X)$, as shown in Figure 18a. After subtracting the estimated background, D-Zero quotes a lower limit on the mass of the top of 103 GeV (95 % CL) in Figure 18b. If the background is not subtracted, a more conservative lower mass limit of 99 GeV is obtained. D-Zero uses a higher order QCD calculation [36] for their production model. If this D-Zero event is assumed to be top , then a Dalitz-Goldstein analysis [37] of the $e\mu$ and leading jets is consistent with m_{top} in the 130-170 GeV range at 90 % CL.

7 Future Programs

Currently Ferimlab is installing a new 400 MeV LINAC which is expected to increase the collider luminosity to $10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$, and to deliver an additional 75 pb^{-1} to both CDF and D-Zero over the next year and a half. With this luminosity, top should be observed if its mass is less than about 150 GeV.

After the collider run, another Fixed Target Physics run is planned, including approved experiments on photoproduction of charm, exclusive $\bar{p} - p$ production of charmonium, hyperon production of charm, high precision K^0 physics, neutrino physics concentrating on neutral current studies of $\sin^2(\theta_W)$ and ρ , di-muon studies of anti-quark distributions in the nucleon, search for relativistic anti-Hydrogen atoms, and extensive test beam programs for Fermilab and SSC experiments.

Further on the horizon is the Main Injector Program to provide even increased collider luminosities of greater than $5 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$, simultaneously with fixed target operations at intensities of up to 3×10^{13} protons per spill, *either* at 120 GeV per 2.9 second cycle with 1.0 second slow spill for proposed K^0 experiments *or* with fast (millisecond) spill for proposed ν -oscillation experiments.

8 Acknowledgements

I would like to thank all these friends who graciously shared their new data or their review compilations to help me prepare this presentation: Joel Butler, Rob Gardner, Jeff Appel, Brad Cox, Lenny Spiegel, Bill Reay, Noel Stanton, Andrzej Zieminski, Dan Kaplan, Fritz deJongh, Claudio Campagnari, Rajendran Raja, Pushpa Bhat, Dan Green, and Stephen Pordes. I'm sorry that there wasn't sufficient time or space to do justice to all this interesting physics.

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Table 1: Recent Fermilab fixed target integrated charmonium cross sections and production fraction of J/ψ via charmonium. Cross section are in units of nanobarns/nucleon.

Experiment Beam $nb/nucleon$	E-672 530 GeV π^- $x_f \geq 0.1$	E-705 300 GeV $x_f \geq 0$			
		π^+	π^\pm	π^-	p
$\sigma(J/\psi_{direct})$	$73 \pm 8 \pm 7$	97 ± 14		102 ± 14	89 ± 12
$\sigma(\chi_c)$	$470 \pm 100 \pm 60$		$432 \pm 127 \pm 32$		$395 \pm 138 \pm 36$
$\sigma(\psi')$	$30 \pm 4 \pm 5$	10 ± 4		8 ± 2	7 ± 2
$F_{\psi \text{ from } \chi_c}$	$0.44 \pm 0.09 \pm 0.03$	0.40 ± 0.04		0.37 ± 0.03	0.30 ± 0.04
$F_{\psi \text{ from } \psi'}$	$0.083 \pm 0.011 \pm 0.010$	0.06 ± 0.02		0.08 ± 0.02	0.08 ± 0.02

Table 2: CDF and D-Zero search for the top quark in the di-lepton mode.

	CDF	D-Zero
1988-89 Data	$4.2 \text{ } pb^{-1}$	
1992-93 Data analyzed	$12 \text{ } pb^{-1}$	$7.5 \text{ } pb^{-1}$
1993-93 Data taken	$21 \text{ } pb^{-1}$	$17 \text{ } pb^{-1}$
Event Selection Criteria:		
$ \eta_{lepton} \leq$	$2.4 (e), 1.0 (\mu)$	$2.5 (e), 1.7 (\mu)$
$E_{\perp}^{\ell 1}, E_{\perp}^{\ell 2} \geq$	20 GeV	15 GeV
missing $E_{\perp} \geq$	25 GeV	20 GeV
$E_{\perp}^{jet_1}, E_{\perp}^{jet_2} \geq$		12.5 GeV
Z^0 background	$m_{\ell^+\ell^-} \neq m_{Z^0}$	$m_{\ell^+\ell^-} \neq m_{Z^0}$
$\ell^+\ell^-$ background	$\Delta\phi \leq 160^\circ$	
$\ell - jet$ isolation cut	yes	yes
μ bremsstrahlung cut		yes

Table 3: Number of top -quark candidates observed, estimated number of background events, and expected signal level for a given m_{top} , for the CDF and D-Zero data samples, event selection, and analyses.

Channel	CDF Observed Events	D-Zero Observed Events	for m_{top} equal to	CDF Expected Signal	D-Zero Expected Signal
e^+e^-	0 event	0 events	80 GeV		$9.8 \text{ } t\bar{t}$ events
$\mu^+\mu^-$	0 event		100 GeV	$7.6 \text{ } t\bar{t}$ events	4.5
$e^\pm\mu^\mp$	1 event	1 event	120 GeV	3.3	2.7
t -candidates obs.	1 event	1 event	140 GeV	1.9	1.5
expected backgrnd.	1.5 event	0.85 event	160 GeV	1.1	

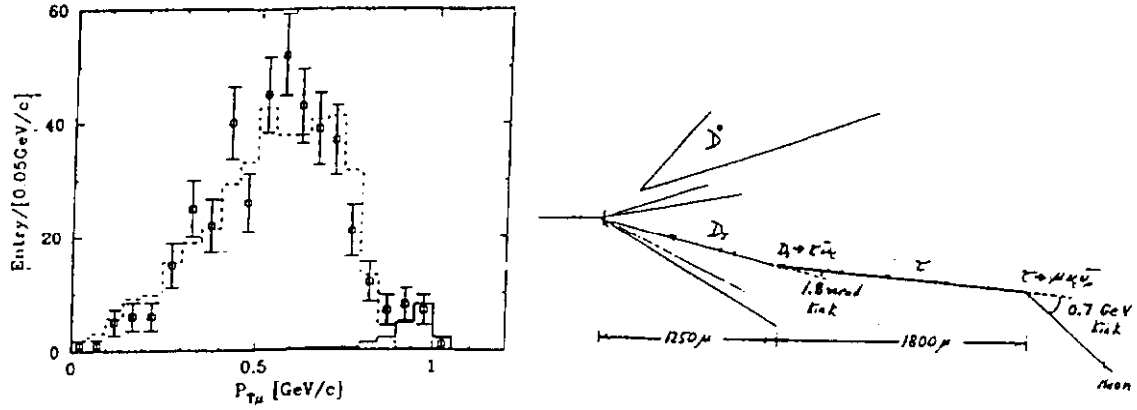
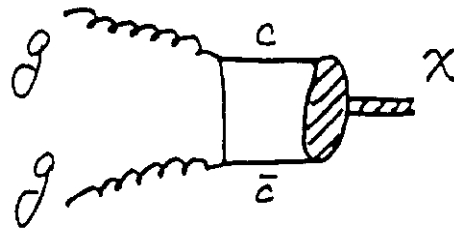


Figure 1: a.) Histogram of $p_{\perp\mu}$, the muon momentum transverse to the decay direction for one-prong muonic decays (kinks) found in the E-653 emulsion. The solid histogram is a simulation of the expected distribution from the leptonic decay $D_s \rightarrow \mu\nu$, while the dashed histogram is a simulation of $D^+ \rightarrow \bar{K}^0 \mu^+ \nu$. b.) Sketch of one of the three E-653 $D_s \rightarrow \tau\mu\tau$ candidates. All decays occur in emulsion.

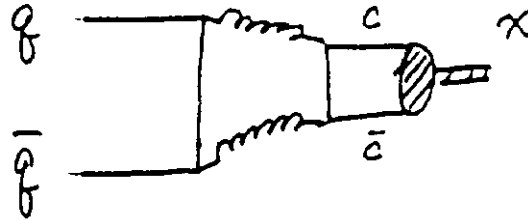
GLUON FUSION

$\chi_{c0}/\chi_{c1}/\chi_{c2} = 15/\epsilon/4$
but minimum direct ψ



QUARK FUSION

$\chi_{c0}/\chi_{c1}/\chi_{c2} = 0/4/1$



EVAPORATION

$\chi_{c0}/\chi_{c1}/\chi_{c2} = 1/3/5$

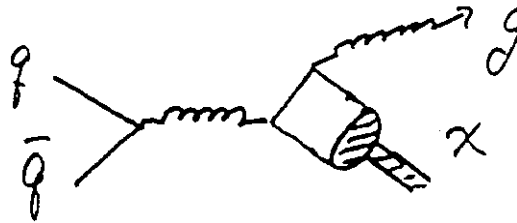


Figure 2: Theoretical models for χ_c production [7].

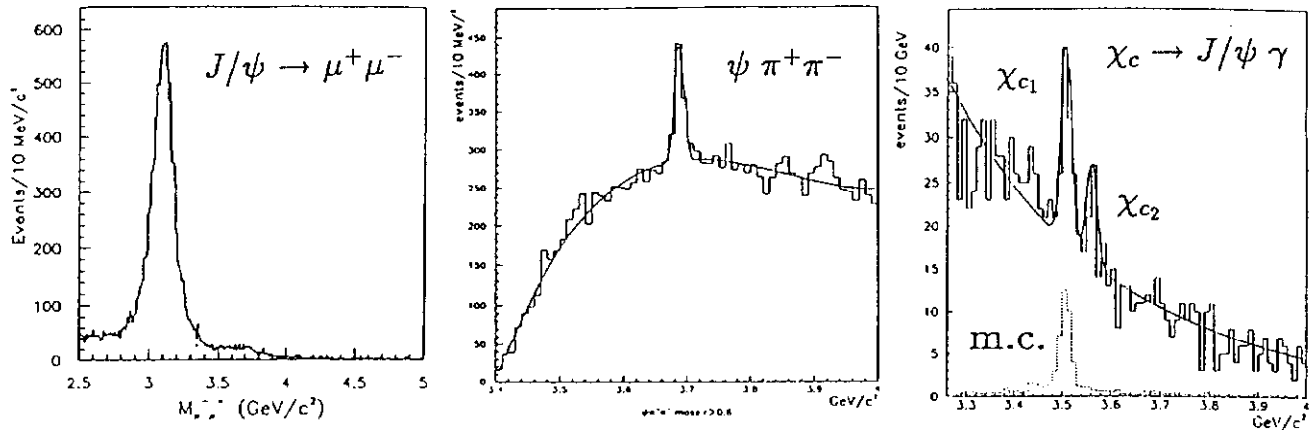


Figure 3: E-672 sample charmonium signals: J/ψ , ψ' , and χ_c .

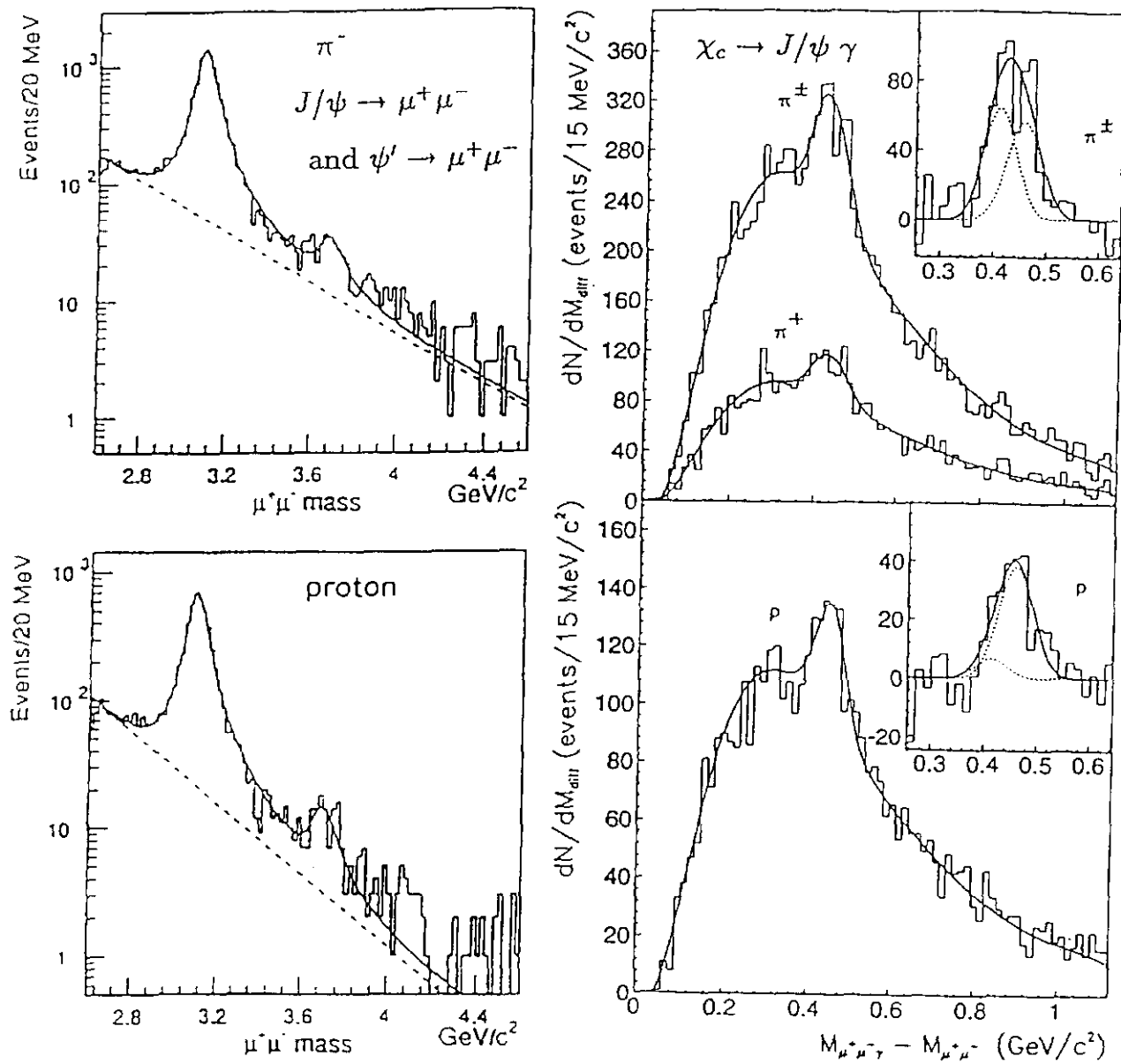


Figure 4: E-705 sample charmonium signals: J/ψ , ψ' , and χ_c .

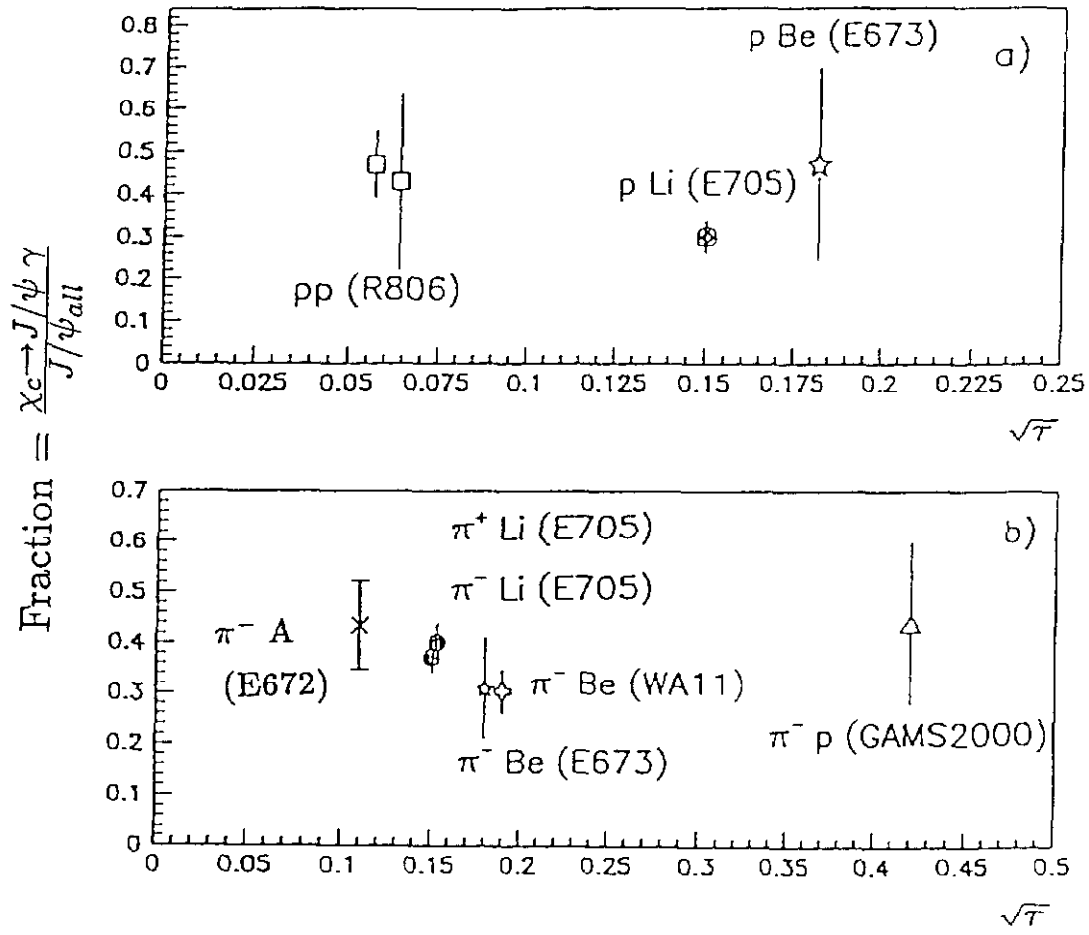


Figure 5: Comparison of hadroproduction fraction of J/ψ via χ_c states.

χ_{c1}/χ_{c2} for Hadronic Production

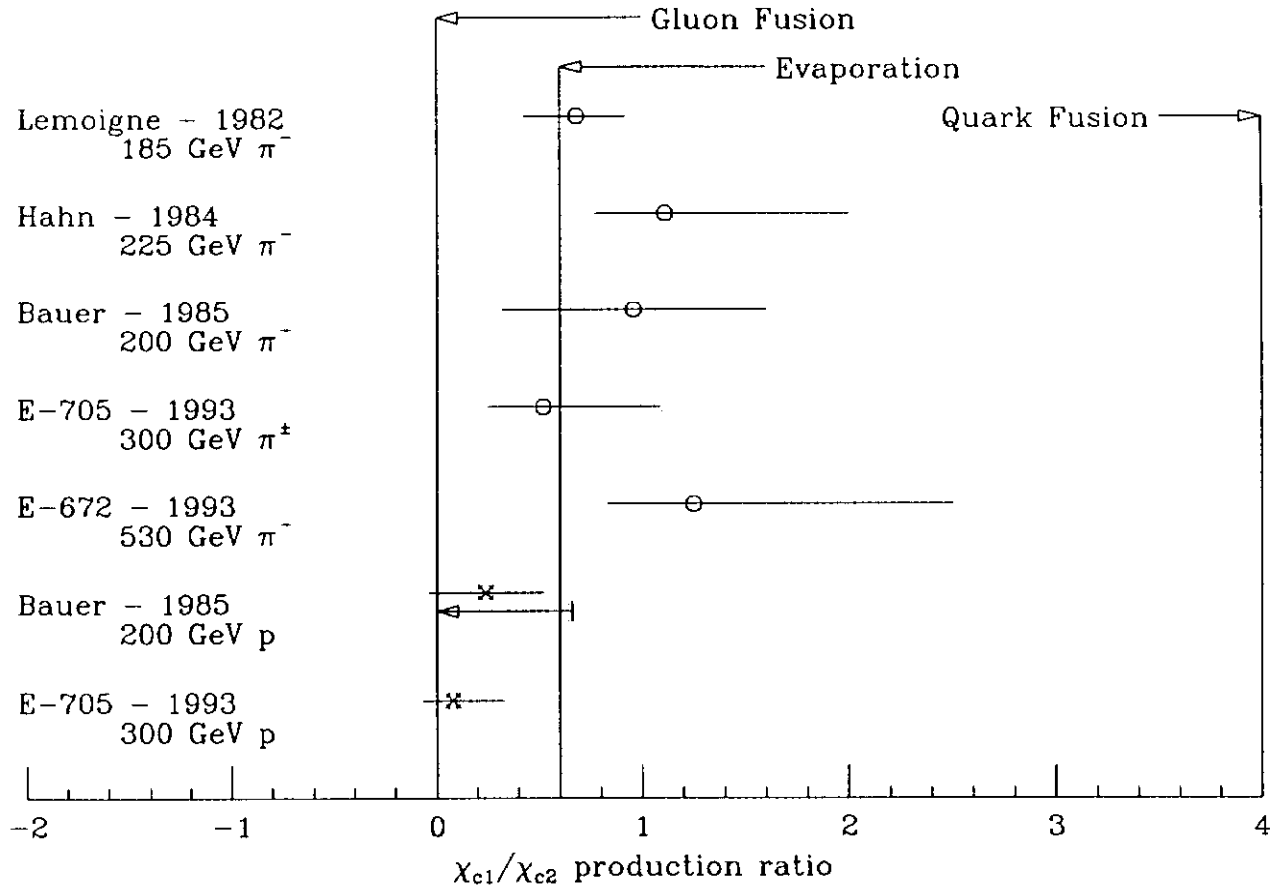


Figure 6: Comparison of hadroproduction ratio of χ_{c1}/χ_{c2} and comparison with predictions of theoretical models [7].

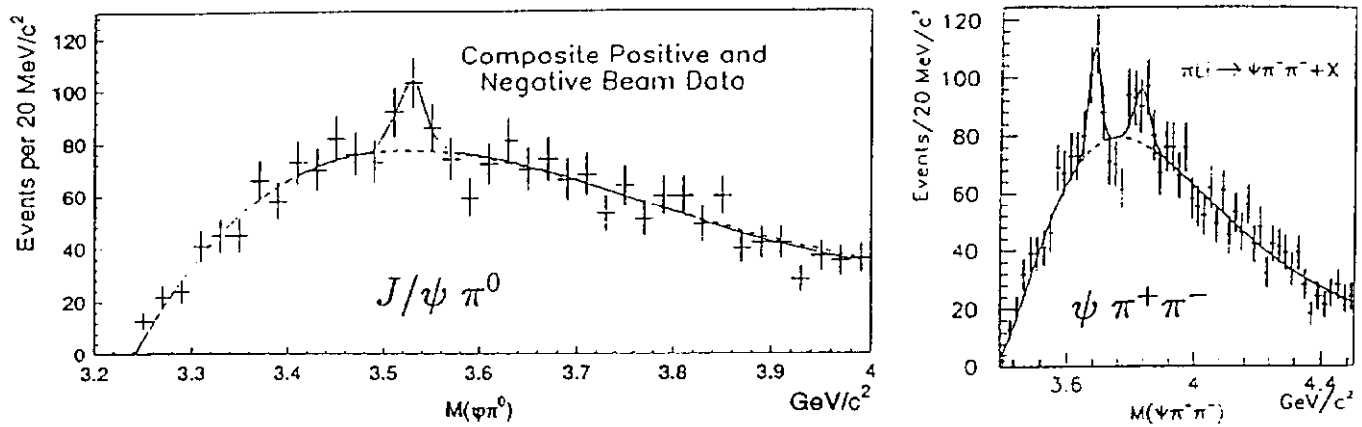


Figure 7: a.) E-705 observation of $\psi \pi^0$ enhancement, interpreted as confirmation of the 1P_1 state of charmonium, and b.) observation of $\psi \pi^+ \pi^-$ enhancement, possibly the first observation of the charmonium 3D_2 state.

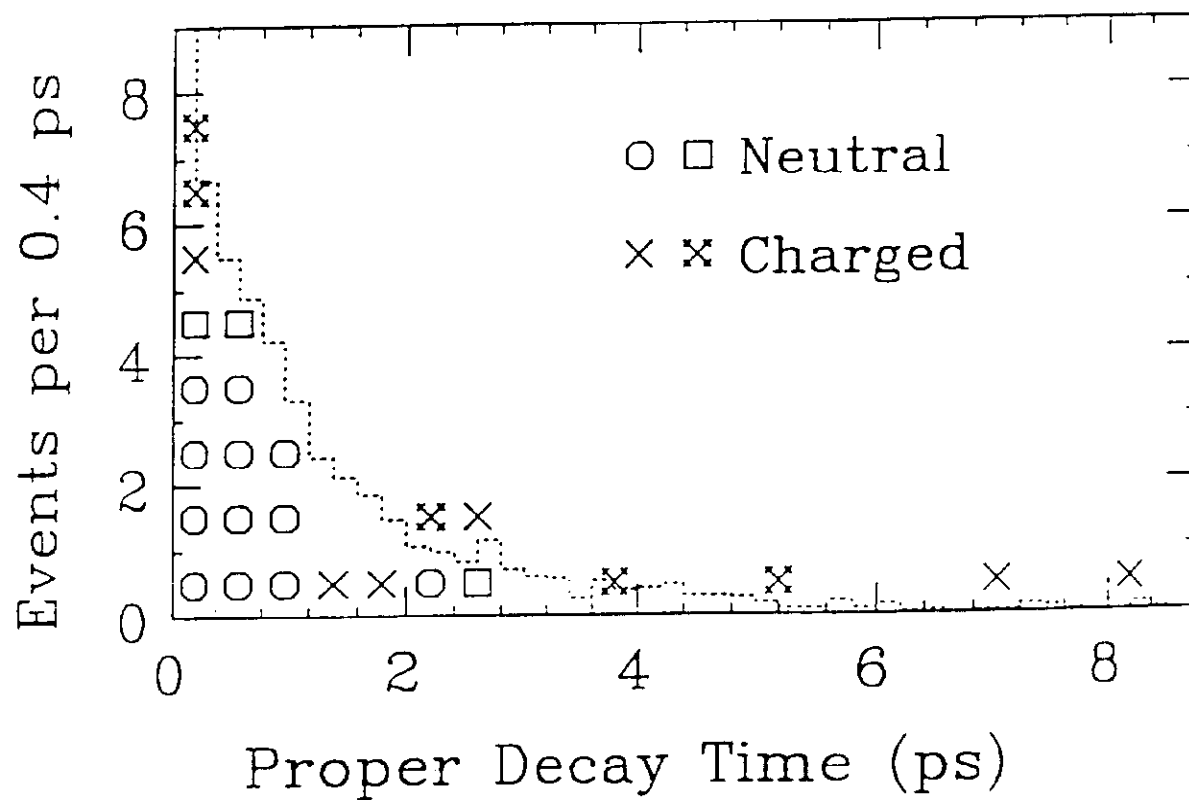


Figure 8: E-653 distribution of proper decay times for charged and neutral b -particles, identified topologically in emulsion.

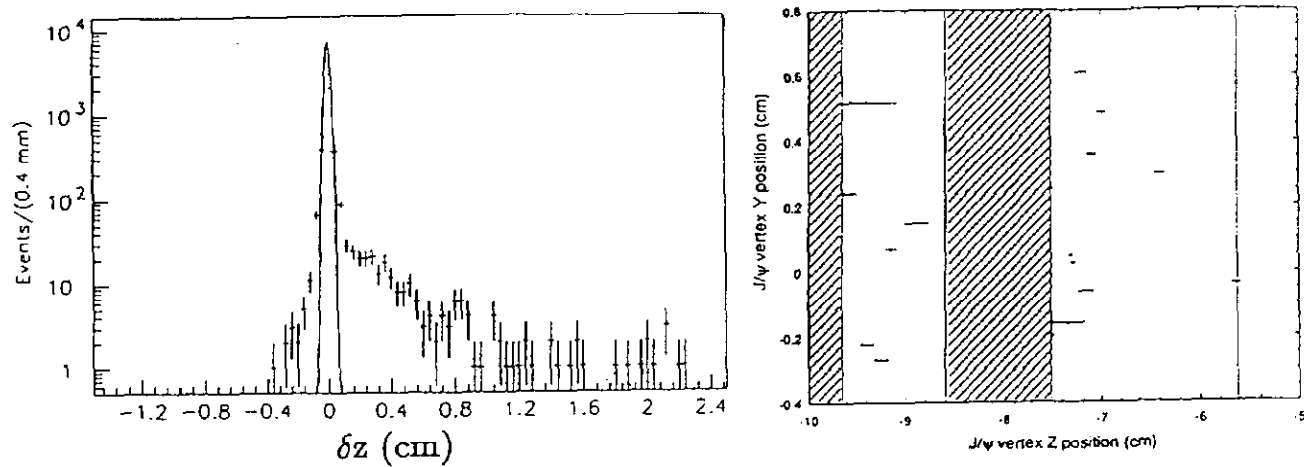


Figure 9: a.) Distribution of E-672 detached J/ψ vertices. b.) Location of secondary J/ψ vertices outside of target material.

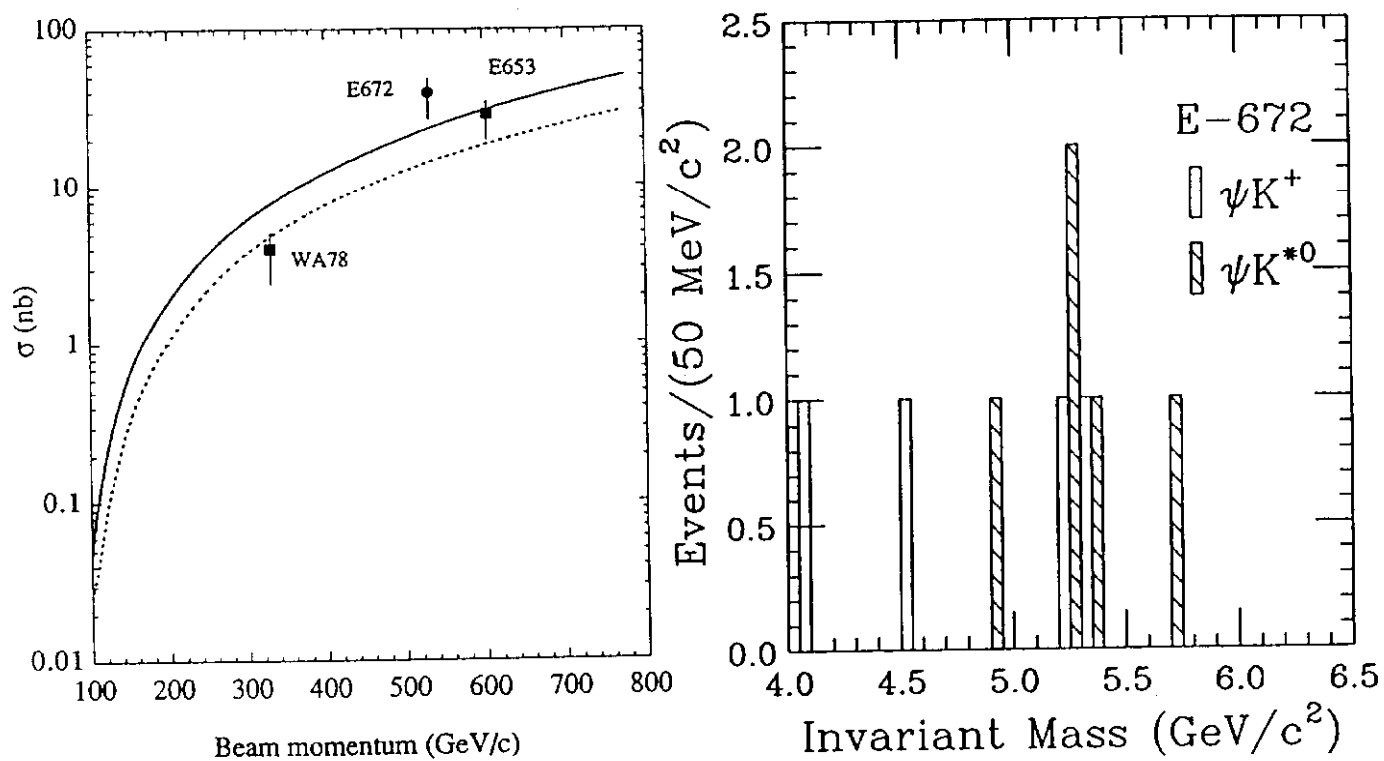


Figure 10: Fixed target physics $b\bar{b}$ cross sections for π^- beams, with range of theoretical predictions [18], and b.) Mass spectrum of E-672 b -particle candidates decaying into ψK^+ or ψK^{*0} .

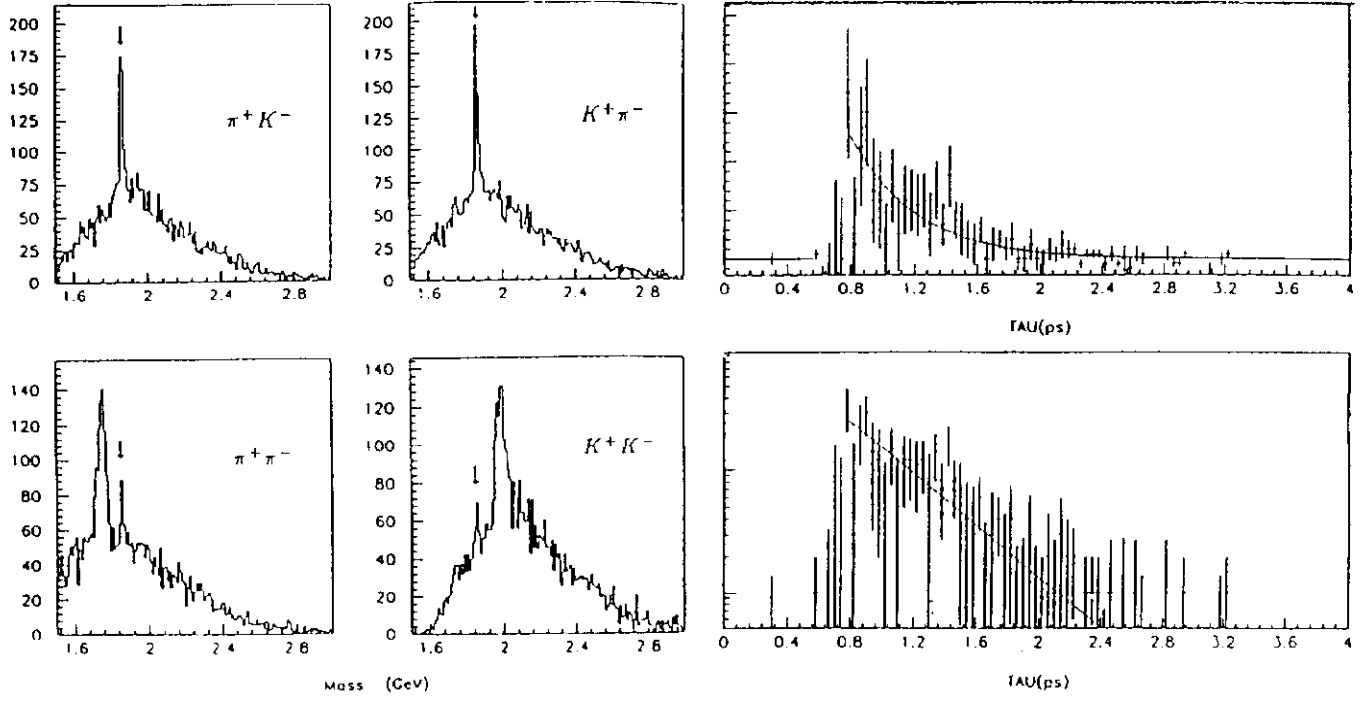


Figure 11: E-789 observation of $D^0 \rightarrow \pi^\pm K^\mp$, $\pi^+\pi^-$, or K^+K^- and observed lifetime distribution with average $\langle \tau(D^0) \rangle = 0.41 \pm 0.03$ psec.

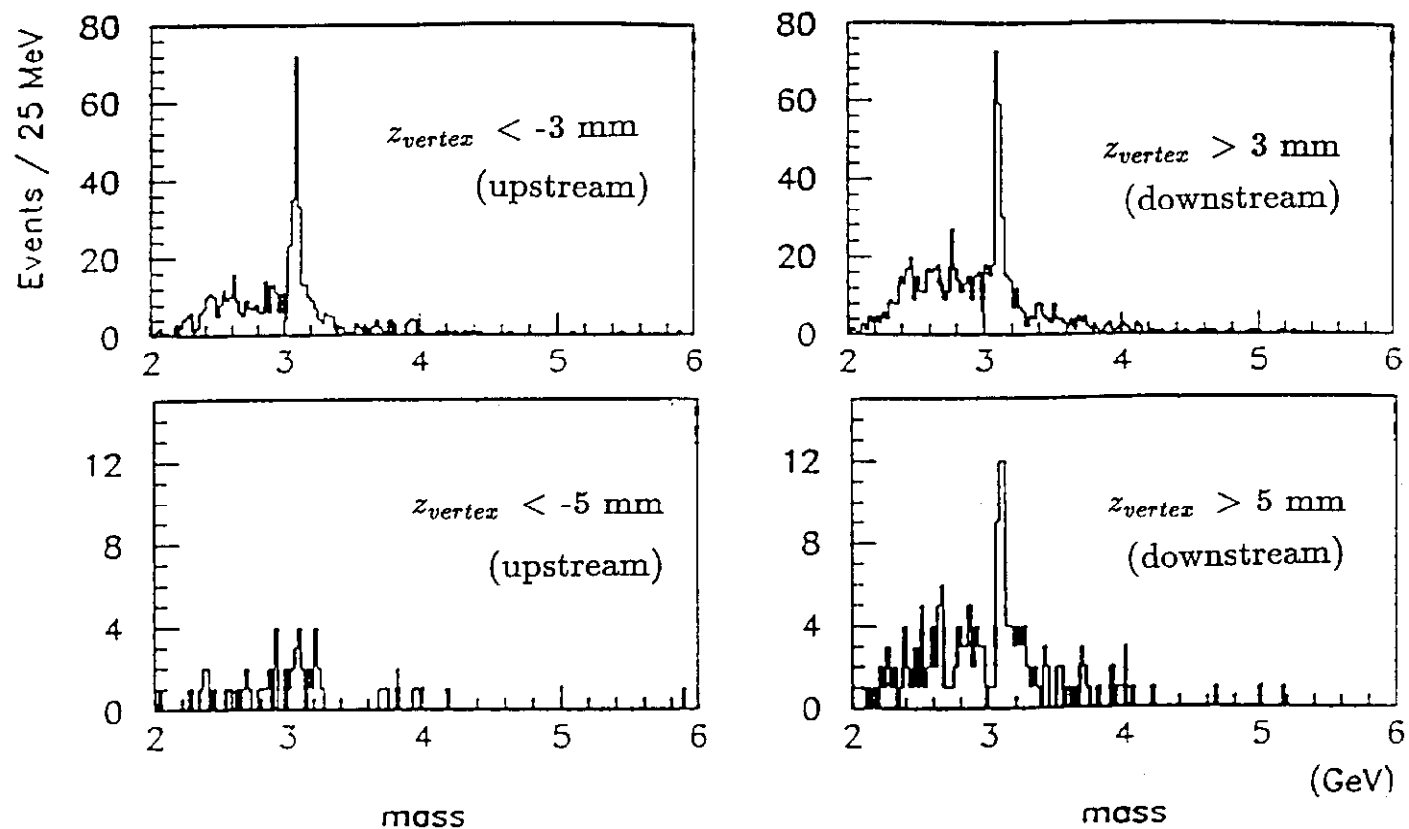


Figure 12: E-789 detached J/ψ vertex b -particle candidate yield as a function of vertex separation cut, both upstream and downstream of the 3 mm diameter Au target.

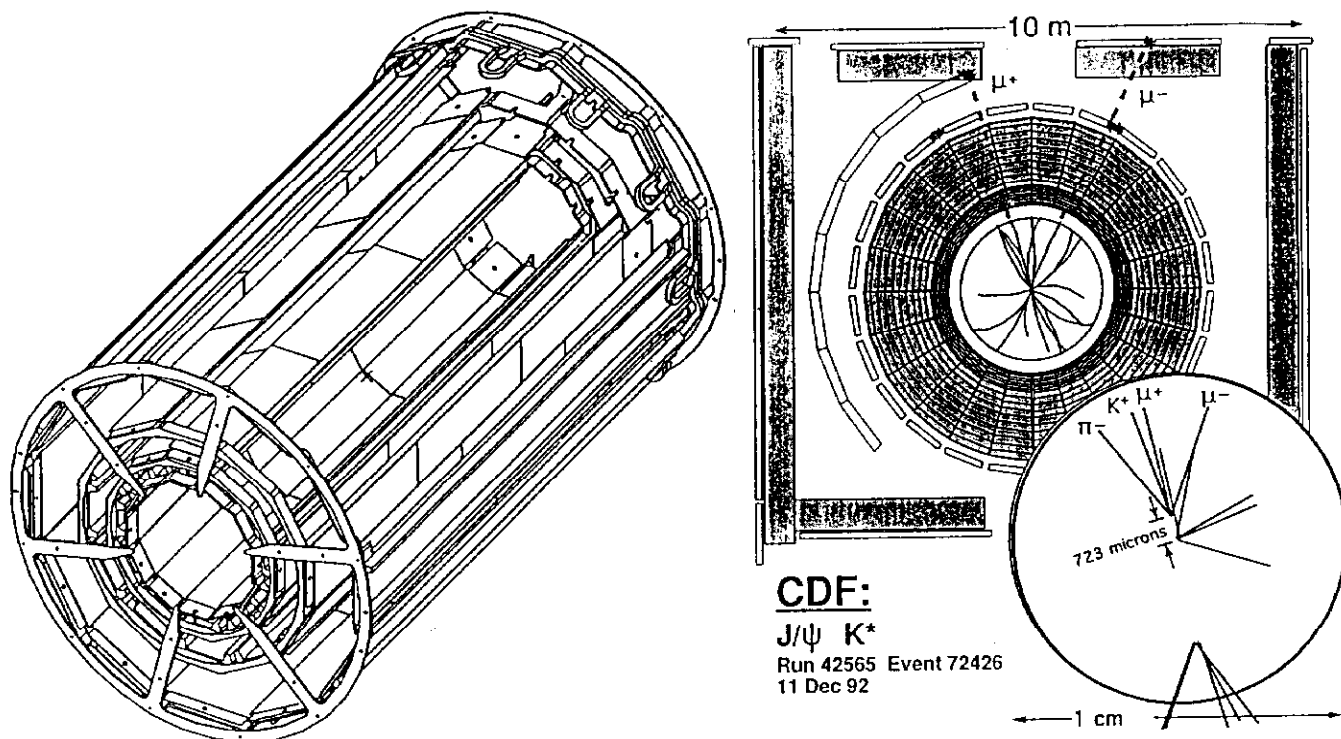


Figure 13: a.) CDF's new SVX high resolution silicon vertex detector (one-half section), and b.) event display using SVX to observe decay of B^0 separated from other vertices.

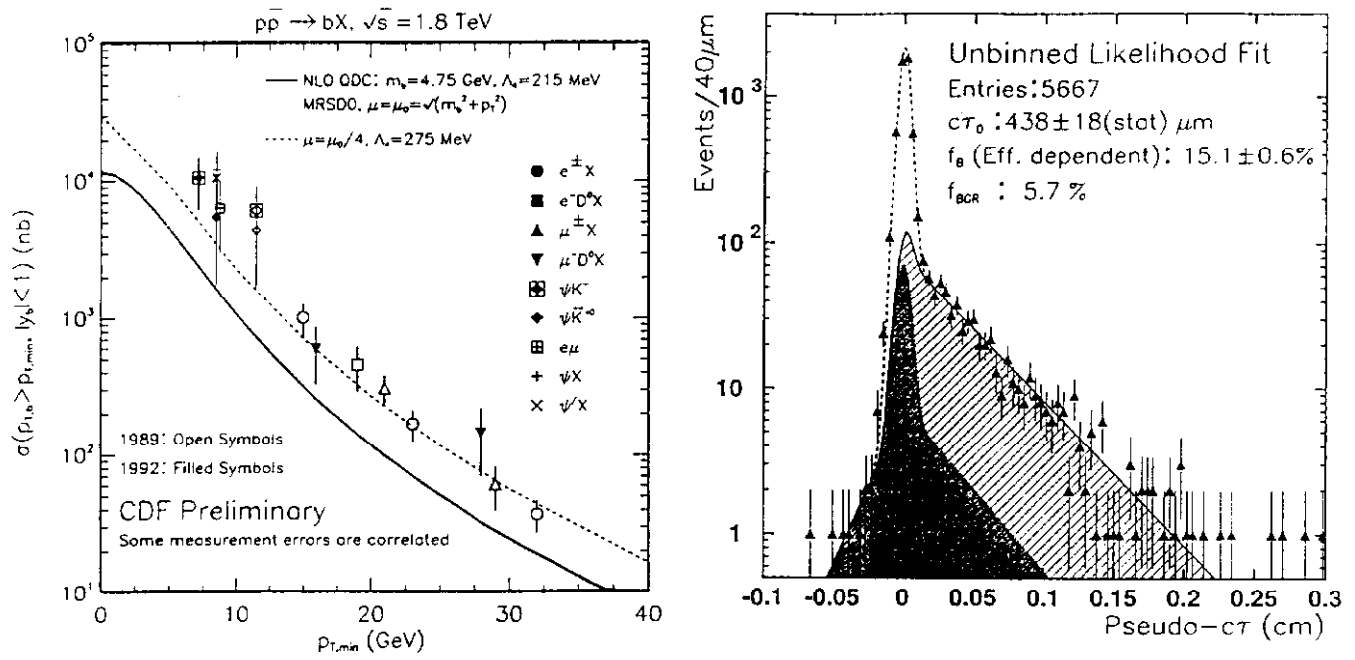


Figure 14: a.) CDF measurements of the cross section for b -particle production at the Fermilab Collider for various channels. The cross sections are integrated above the minimum p_{\perp} indicated on the lower axis. b.) CDF observation of the pseudo-proper time distribution for detached vertex J/ψ (data points), sideband background (shaded), and background subtracted signal (curve).

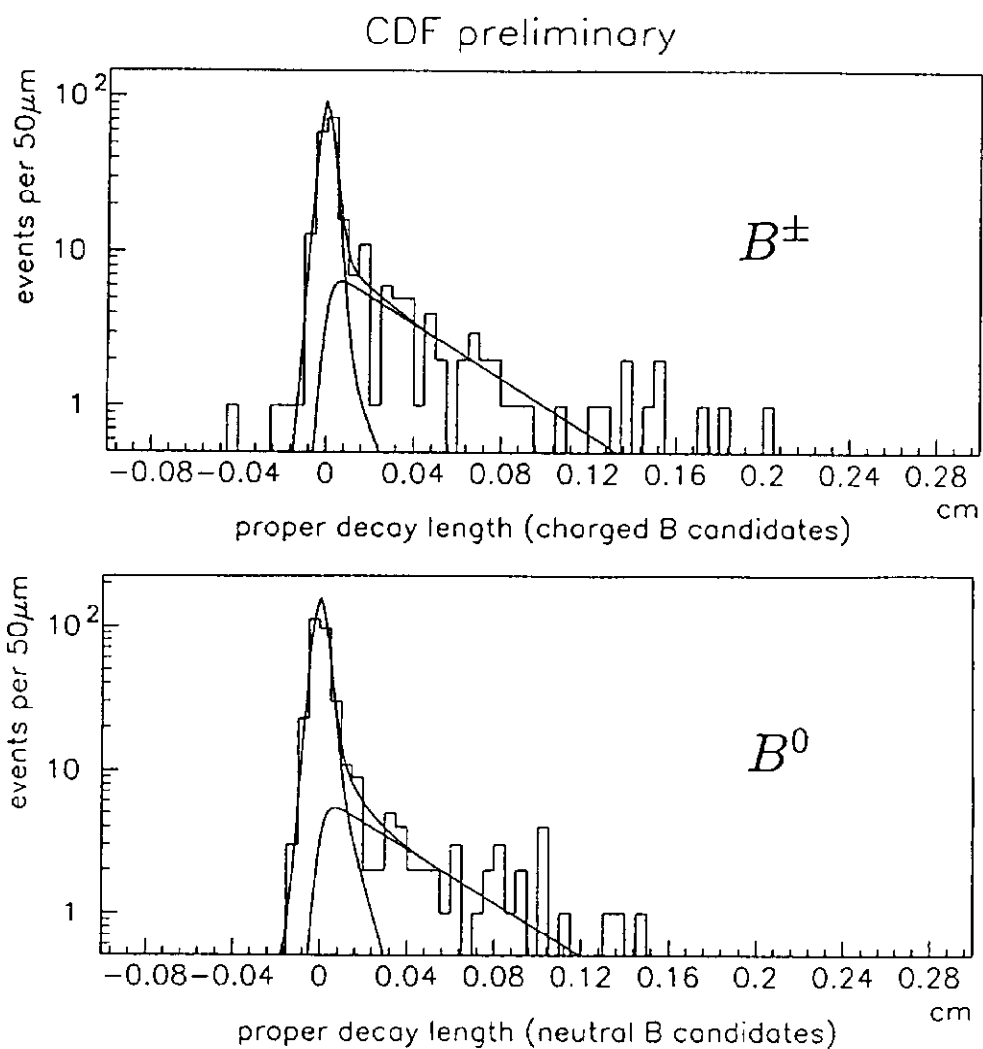


Figure 15: Proper time distributions for B^+ and B^0 candidates by CDF. The curves include the signal, the sideband backgrounds, and their sum.

$$B^+ \rightarrow J/\psi + K^+$$

$$79.5 \pm 11.4 \text{ events}$$

$$m_{B^+} = 5278.2 \pm 2.6 \text{ MeV}/c^2$$

$$B_d^0 \rightarrow J/\psi + K^{*0}$$

$$43.7 \pm 8.7 \text{ events}$$

$$m_{B_d^0} = 5279.6 \pm 2.9 \text{ MeV}/c^2$$

$$B_s^0 \rightarrow J/\psi + \phi$$

$$14.0 \pm 4.7 \text{ events}$$

$$m_{B_s^0} = 5383.3 \pm 4.5(\text{stat}) \pm 5.0(\text{syst}) \text{ MeV}/c^2$$

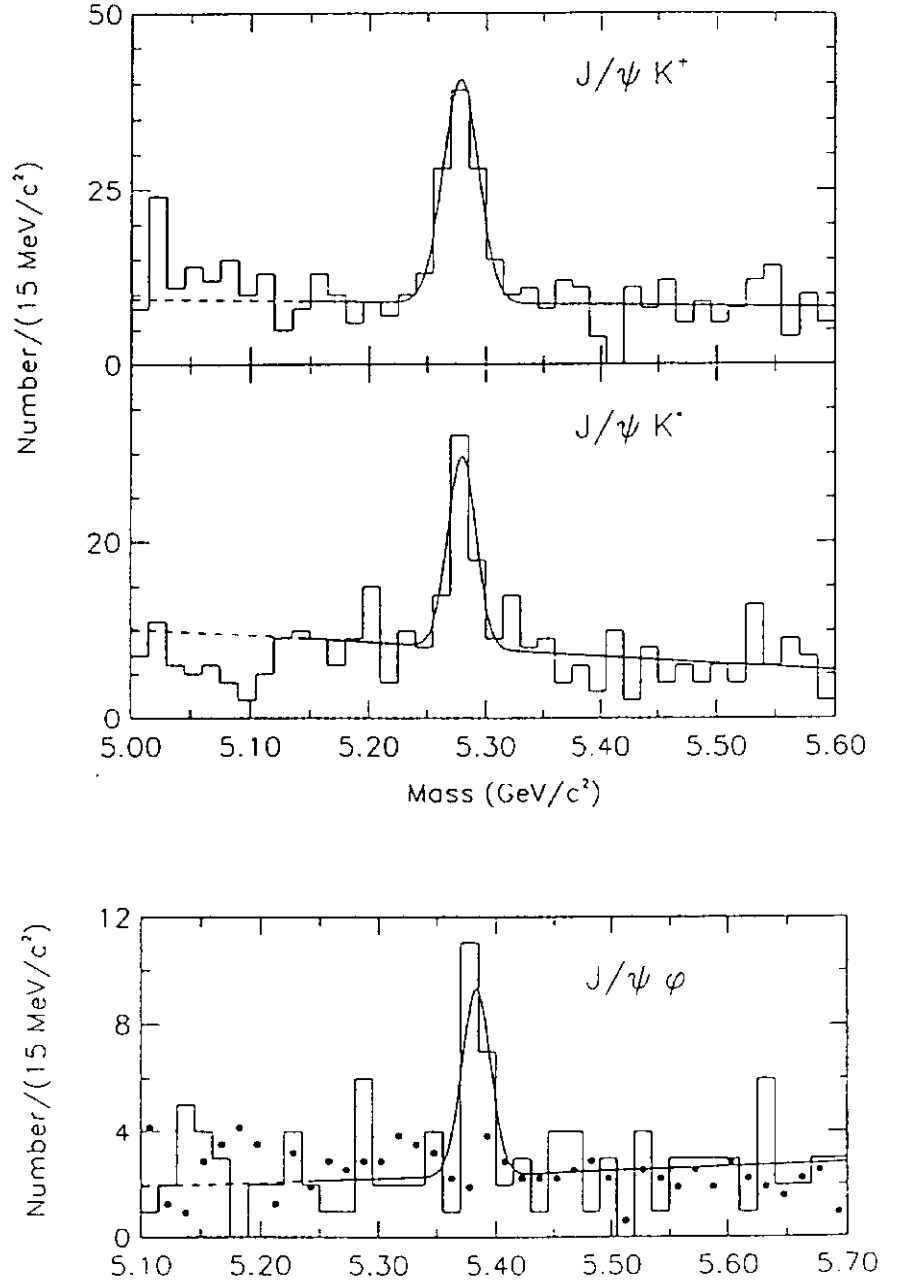


Figure 16: CDF mass spectra for $B^+ \rightarrow J/\psi K^+$, $B_d^0 \rightarrow J/\psi K^{*0}$, and $B_s^0 \rightarrow J/\psi \phi$.

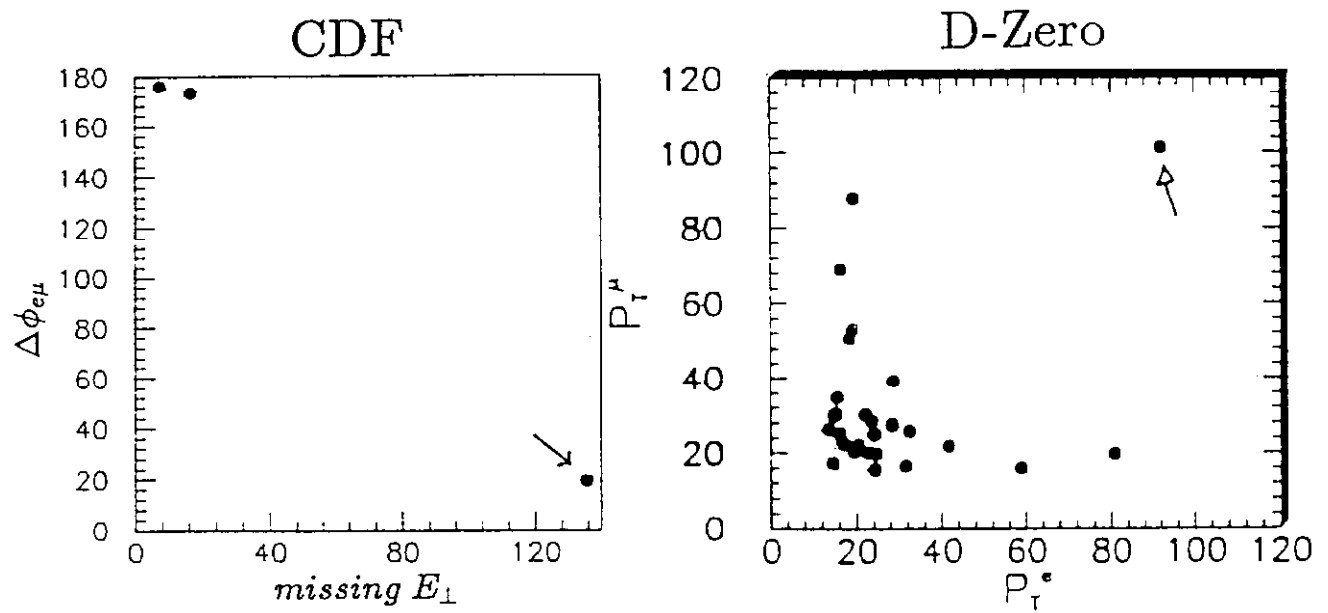


Figure 17: *top*-quark $e - \mu$ candidate events remaining after applying event selection criteria of Table 2: a.) in the $\Delta\phi_{e\mu}$ vs. *missing* E_{\perp} plane for CDF, and b.) in the P_T^e vs. P_T^{μ} plane for D-Zero. One remaining candidate event for each experiment is clearly separated.

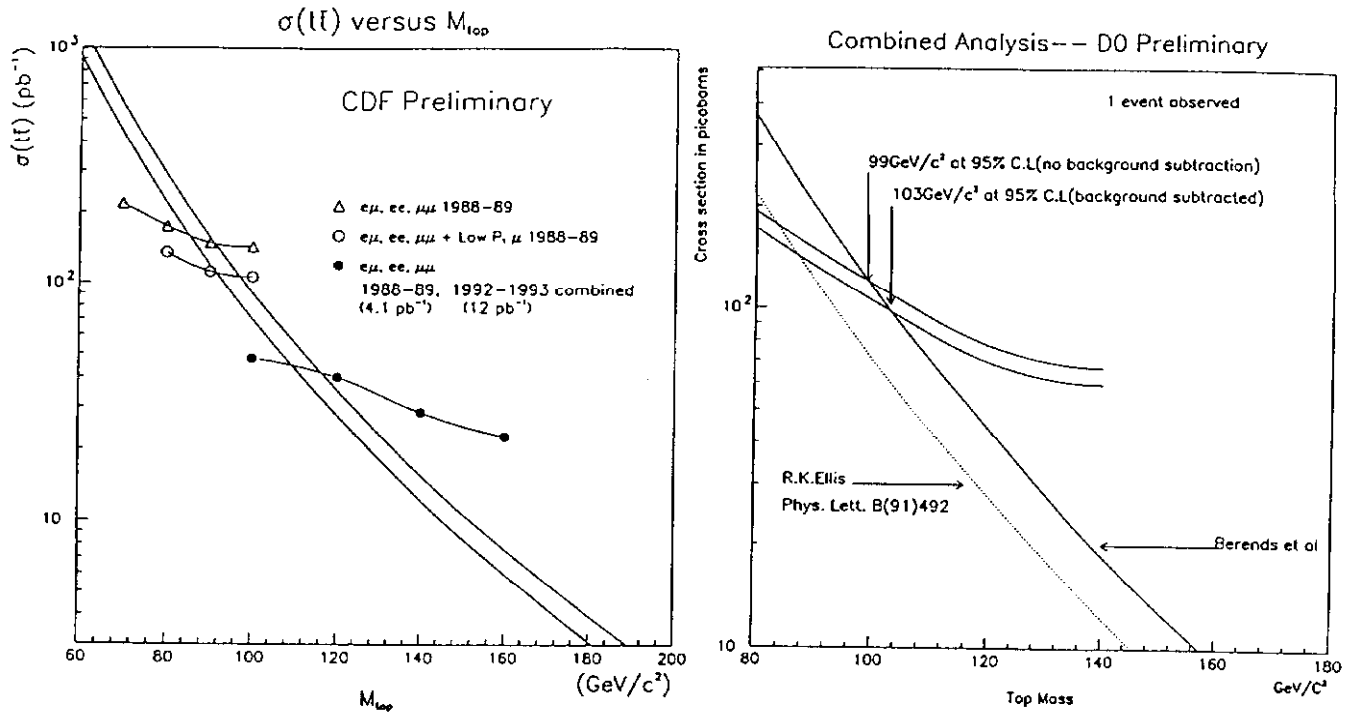


Figure 18: a.) CDF 95 % CL lower limit on $m_{top} > 108 \text{ GeV}$, based on the 1988-89 and one half of the 1992-93 di-lepton data samples. b.) D-Zero 95 % CL lower limit on $m_{top} > 103 \text{ GeV}$, background subtracted, based on one half of the 1992-93 di-lepton data sample.